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## SUBMISSION OF PRIORITY DOCUMENT(S)

Assistant Commissioner for Patents
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Dear Sir:

The Applicants enclose herewith one certified copy of each of the following applications:

| Application No. | Filing Date | Country |
|---|---|---|
| PA 2000 01125 | 21 July 2000 | Denmark |
| PA 2000 01405 | 21 September 2000 | Denmark |
| PA 2001 00227 | 12 February 2001 | Denmark |
| PA 2001 01014 | 28 June 2001 | Denmark |

Applicants hereby claim the benefit under Title 35, United States Code § 119 of these applications.

Respectfully submitted,

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This is to certify the correctness of the following information:

The attached photocopy is a true copy of the following document:

- The specification, claims and figures as filed with the application on the filing date indicated above.



**Patent- og Varemærkestyrelsen**
Erhvervsministeriet

Taastrup 07 August 2001

Inge-Lise Sørensen
Head Clerk

Modtaget
21 JULI 2000
PVS

# DISPERSION MANIPULATING FIBRE

Field of the invention:

The present invention relates to optical fibres and especially to optical fibres having micro-structures in core and/or cladding region(s).

Background of the invention:

The dispersion properties of conventional optical fibres are receiving a continuously high research interest in connection with high-capacity optical communication, soliton propagation, and control of non-linear effects. Accordingly, there is a strong interest in realizing new types of optical fibres that may provide new dispersion properties or may counteract some of the undesired dispersion properties of existing fibres.

Recently a new type of optical fibre that is characterized by a so-called microstructure has been proposed. Optical fibres of this type (which are referred to by several names – as e.g. micro-structured fibres, photonic crystal fibre, holey fibre, and photonic bandgap fibres) have been described in a number of references, such as WO 99/64903, WO 99/64904, and Broeng et al (see Pure and Applied Optics, pp.477-482, 1999) describing such fibres having claddings defining Photonic Band Gap (PBG) structures, and US patent no. 5,802,236, Knight et al. (see J. Opt. Soc. Am. A, Vol. 15, No. 3, pp. 748-752, 1998), Monro et al. (see Optics Letters, Vol.25 (4), p.206-8, February 2000) defining fibres where the light is transmitted using modified Total Internal Reflection (TIR). This application covers fibres that may guide by both physical principles and we shall use the term micro-structured fibres to generally describe these fibres.

Micro-structured fibres are known to exhibit dispersion properties that are unattainable in conventional optical fibres (see e.g. Ranka et al., Optics Letters, Vol. 25, No. 1, pp.25-27, 2000, Broderick et al. Optics Letters, Vol. 24, No. 20, pp. 1395-1397, 1999, Mogilevtsev et al. Optics Letters, Vol. 23, No. 21, pp. 1662-1664, 1998). These properties include shifting the zero dispersion wavelength below 1.3μm. This has e.g. in the above-cited Ranka-reference been utilized for super-continuum generation of light over a very broad frequency range (covering visible to near-infrared wavelengths). The development of such white-light generators using micro-structured fibres was made possible through the design of micro-structured fibres with high anomalous waveguide dispersion at visible wavelength – and it has fuelled a large research interest into non-linear effects in micro-structured

fibres (Fedotov et al. JETP Letters, Vol. 71, No. 7, pp. 281-284, 2000, Wadsworth et al. CLEO 2000, Paper PD1.5, 2000). The above-cited references all describe fibres with zero dispersion wavelength shifted below 1.3μm. The fibres are characterized by a relatively high cladding air-filling fraction – air hole diameters, *d*, of more than 0.45 times the centre-to-centre distance between two nearest air holes, Λ, and they have all a solid core. The size of the core is relatively small – about 1.5μm in diameter. It is a disadvantage of the prior art fibres with zero-dispersion wavelength shifted below 1.3μm that they are not strictly single-mode at visible wavelengths, but support a few (or more) guided modes. In the above-cited reference by Ranka et al., it is demonstrated that for relatively short fibre lengths, the fundamental mode of such fibres may be considered undisturbed by any higher order guided modes (i.e. there is a low coupling coefficient between the fundamental and the higher order modes). However, for guidance over longer fibre lengths (i.e. hundred of meters) it is a disadvantage of the prior art fibres with zero dispersion wavelength shifted below 1.3 μm that they are not strictly single mode at visible wavelengths. It is a further disadvantage of the prior art fibres with zero dispersion wavelength below 1.3 μm that they will be highly multimode at visible wavelengths if the core size is increased above 2 μm. It would be an advantage if fibres with zero dispersion wavelength shifted below 1.3 μm could be realized so as to have a core that was comparable in size to that of standard transmission optical fibres (i.e. to have a core of around 5 micron in diameter).

Another important aspect of micro-structured fibres is that they may exhibit normal dispersion (or so-called negative dispersion) at near-infrared wavelengths. Fibres with large negative dispersion at 1.55 μm are attractive for use as insertion-components in existing optical fibre communication links, as they may be used to compensate the positive dispersion around 1.55 μm of already installed standard transmission fibres (i.e. fibres that are designed to operate in the second telecommunication window and have a zero dispersion wavelength at 1.3μm).

Monro et al. have presented micro-structured fibres having dispersion values of about –30 ps/nm/km at 1.55 μm (see Journal of Lightwave Technology, Vol. 17, No. 6, pp.1093-1102, 1999). The fibres presented by Monro et al. are characterized by a solid core surrounded by micro-structured cladding with a close-packed arrangement of identical air holes. The cladding holes have a size d/Λ around 0.2. It is a disadvantage of the fibres presented by Monro et al. that the dispersion is not more negative than –30 ps/nm/km.

DiGiovanni et al. (see US patent no. 5,802,236) have presented micro-structured fibres that provide significantly larger negative dispersion at near-infrared wavelengths. DiGiovanni et al. disclose micro-structured fibres that are characterized by a core and a micro-structured cladding. The cladding consists of inner and outer cladding features, thereby forming an inner and an outer cladding region. Both the inner and outer cladding of the fibres has an effective index that is lower than the core refractive index at all wavelengths. The features of the inner cladding region (preferably air holes) act to lower the effective refractive index compared to the effective refractive index of the outer cladding region. Hence, the fibres disclosed by DiGiovanni have a so-called "depressed" cladding design. The use of depressed cladding regions is well-known from the development of conventional dispersion compensating fibres (see e.g., M.Monerie, Propagation in doubly clad single-mode fibres, IEEE Journal of Quantum Electronics, vol.QE-18, no.4, April 1982, pp.535-542). To those skilled in the art, it will be recognised that in order to increase the negative dispersion of the fibres disclosed by DiGiovanni et al., the size of the cladding features must be increased. Digiovanni et al. disclose fibres that have dispersion of up to –1700 ps/nm/km. It is a disadvantage of the fibres disclosed by DiGiovanni that the depressed cladding design does not allow to increase the inner cladding feature size so as to obtain negative dispersion of more than –2500 ps/nm/km. This latter limit of maximum obtainable negative dispersion was predicted by Birks et al. (see Photonics Technology Letters,Vol. 11, No. 6, pp. 674-676, 1999). Birks et al. studied the fundamental limits of negative dispersion that can be obtained in solid core micro-structured fibres made of pure silica and air. Birks et al. argue in the above-cited reference that by increasing the void size (air holes) the negative dispersion of micro-structured fibres is generally increased. Hence, an ideal micro-structured fibre (with respect to negative dispersion) consists - according to Birks et al. - merely of a thin silica rod (the fibre core) surrounded by air. Hence, Birks et al. made a prediction of the maximum obtainable negative dispersion based on the study of a solid silica rod surrounded completely by air (this case corresponds to the inner cladding features of the fibres disclosed by DiGiovanni et al. being so large that they overlap each-other). For such an ideal micro-structured fibre, Birks et al. found a dispersion of –2000 ps/nm/km. This result has been taken as the maximum obtainable negative dispersion that can be obtained using silica-based optical fibres. It is a disadvantage of the fibres disclosed by Birks et al. that a negative dispersion of more than –2500 ps/nm/km cannot be obtained. It is a further disadvantage of the fibres disclosed by Birks et al. and of DiGiovanni et al. that

the fibre core must be very small (about 1μm or less in diameter) in order to ensure single mode operation at near-infrared wavelengths while exhibiting large negative dispersion.

The present invention provides fibres that are substantially single mode at visible wavelengths while having zero dispersion shifted below 1.3 μm. This application further discloses fibres that are strictly single mode, have a zero dispersion wavelength below 1.3 micron, and a core diameter of more than 2 μm.
This application discloses micro-structured fibres that have dispersion significantly more negative than –2500 ps/nm/km. The present inventors have realized that it is advantageous to turn up-side-down the usual design rules for realization of fibre with large negative dispersion – and to design fibres with a so-called "raised", micro-structured, inner cladding region. As documented in this application, it becomes possible to realise micro-structured fibres with negative dispersion of up to –4500 ps/nm/km. This application describes in detail the design-route that the present inventors have found in order to realize such fibres and discloses a number of preferred embodiments of fibres according to the present invention.

<u>Glossary and definitions:</u>
In this application we distinguish between "refractive index" and "effective refractive index". The refractive index is the conventional refractive index of a homogeneous material. In this application we consider mainly optical wavelengths in the visible to near-infrared regime (wavelengths from approximately 400nm to 2μm). In this wavelength range most relevant materials for fibre production (e.g. silica) may be considered mainly wavelength independent, or at least not strongly wavelength dependent. However, for non-homogeneous materials, such as micro-structures, the effective refractive index is very dependent on the morphology of the material. Furthermore the effective refractive index of a micro-structure is strongly wavelength dependent – much stronger than the refractive index of any of the materials composing the micro-structure. The procedure of determining the effective refractive index of a given micro-structure at a given wavelength is well-known to those skilled in the art (see e.g. Jouannopoulos et al, "Photonic Crystals", Princeton University Press, 1995 or Broeng et al, Optical Fiber Technology, Vol. 5, pp.305-330, 1999). The present invention takes advantage of specific micro-structure morphologies and their strong wavelength dependency in a novel manner and discloses fibres where the effective indices of the core and cladding regions are varying with respect to each-other in an untraditional way. Most importantly, there exists for the fibres,

disclosed in this application, specific wavelengths – so-called "shifting" wavelengths - for which the difference between the effective indices of core and cladding regions may change sign. The present inventors utilize this property to realize micro-structured fibres with strong dispersion around the shifting wavelengths.

Usually a numerical method capable of solving Maxwell's equation on full vectorial form is required for accurate determination of the effective refractive indices of micro-structures. The present invention makes use of employing such a method that has been well-documented in the literature (see previous Joannopoulos-reference). In the long-wavelength regime, the effective refractive index is roughly identical to the weighted average of the refractive indices of the constituents of the material. For micro-structures, a directly measurable quantity is the so-called filling fraction that is the volume of disposed features in a micro-structure relative to the total volume of a micro-structure. Of course, for fibres that are invariant in the axial fibre direction, the filling fraction may be determined from direct inspection of the fibre cross-section.

<u>Summary of the invention:</u>

The problem to be solved by the invention is to be able to guide light in single-mode micro-structured fibres, while being able to either shift the zero dispersion wavelength to a wavelength shorter than 1.3 μm or to obtain a large negative dispersion value around 1.55μm. The present inventors have discovered that the prior art fibres with a solid core require small core diameters in order to obtain single-mode operation and large negative dispersion. The present invention discloses a method for obtaining large negative dispersion, while maintaining a core diameter comparable to that of standard optical fibres. Further, the use of a depressed cladding – as disclosed in the prior art – is not optimum for realising fibres with large negative dispersion at near-infrared wavelengths. The present inventors have found that micro-structured fibres can be improved with respect to increasing the dispersion (both to large negative or large positive values) if the fibres have a micro-structured core region with a feature spacing that is smaller than the cladding feature spacing and/or if the fibre is designed with two cladding regions where the inner cladding region is micro-structured and has an effective refractive index that is larger than the outer cladding region (the inner cladding region should have a lower filling fraction than the outer cladding region).

Large air holes in cladding of micro-structured fibres generally allow a higher degree of flexibility when tailoring the dispersion properties of the fibres. It is, therefore, desirable to realize micro-structured fibres with large air holes. The main problem for the fibre designs disclosed in the prior art is, however, that above a certain air hole size, the fibres may become multi-mode. This present invention includes a way of realizing strictly single-mode micro-structured fibres with large air holes, by using micro-structuring of the core region and/or various dopants in the high-index composite of the micro-structured fibre (this being either in the core or in the cladding – or in both). The invention covers two main aspects, namely fibres with micro-structured core regions, where the core features are smaller and more closely spaced than the cladding features and it covers fibres with a so-called raised, inner, micro-structured cladding region. The invention allows realization of substantially single-moded fibres - with core sizes comparable to conventional optical fibres - which can significantly increase the flexibility for manipulating the dispersion in optical fibre communication systems.

In a first aspect, the invention is embedded in an article (which e.g., can be used in an optical fibre communication system) that comprises a micro-structured fibres that comprises a core region that comprises a multiplicity of spaced apart core features that are elongated in the fibre axial direction and disposed in a core material, the core being surrounded by a cladding material that comprises a multiplicity of spaced apart cladding features that are elongated in the fibre axial direction and disposed in a first cladding material, the core features being closer spaced than the cladding features.

The present invention includes micro-structured fibres, where the elongated features may be either non-periodically or periodically distributed. Hence, when we are discussing the spacing of elongated elements, we will mean the centre-to-centre distance between two neighbouring features. For periodically distributed features, this centre-to-centre spacing is easily determined, and is e.g. for a close-packed arrangement of the features identical to the pitch of the periodic structure. For non-periodic distributions, the centre-to-centre spacing should be taken as the average centre-to-centre distance between neighbouring features. For special distributions, e.g. in the case of a very low number of features, the centre-to-centre spacing should be taken as the smallest centre-to-centre distance between neighbouring features in the relevant region.

In a preferred embodiment, the core has a diameter larger than 2 μm. For telecom applications, generally a core size in the range from about 2 μm to 10 μm is desired. For high-power applications, a larger core size is desired such as from about 10 μm to 50 μm.

In a further preferred embodiment, the cladding features should have a diameter that is larger than 0.45 times the cladding feature spacing, such as a diameter larger than 0.6 times the cladding feature spacing, such as larger than 0.9 times the cladding feature spacing. Also it is preferred that cladding features occupy at least 25% of the cross-section of the cladding region, such as more than 40%, such as more than 50%, such as more than 60%, such as more than 70%, such as more than 80%.

It is further preferred that in order to guide light in a single mode with strong dispersion, that the core features occupy more than 5% of the cross-section of the core region, such as more than 10%, such as more than 25%, such as more than 50%, such as more than 75%.

In a further preferred embodiment the cladding features are periodical cladding features, this may e.g. be by close-packing, which provides intrinsically the largest void filling fraction.

In a further preferred embodiment the number of core features is larger than 2, such as larger than 5, such as larger than 17.

In a further preferred embodiment the core features are periodical core features.

In a further preferred embodiment the spacing of the core features and of the cladding features are in the range of about 0.2 μm to 50 μm.

Commonly it is preferred to realise the fibres with core material and/or the cladding material being silica.

It will be further advantageous to have the refractive index of the core material to be lower than the refractive index of the first cladding material.

Commonly, the core features and/or the cladding features are voids. These voids may depending on the specific application of the fibre contain air, another gas, or a vacuum.

In a second aspect, the invention is embedded in an article (e.g. in an optical fibre communication system) that comprises a micro-structured optical fibre having an axial direction and a cross section perpendicular to said axial direction, the optical fiber comprising a core region surrounded by a cladding region that comprises a multiplicity of spaced apart cladding features that are elongated in the axial direction and disposed in a first cladding material, the core region having an effective refractive index and the cladding features having a refractive index that differs from a refractive index of the first cladding material, and the cladding region comprises an inner cladding region surrounding the core region and an outer cladding region surrounding the inner cladding region where the inner and outer cladding regions having effective refractive indices $N_i$, and $N_o$, respectively, with $N_i > N_o$, and the cladding features in the inner cladding region having smaller size in cross section than the cladding features in the outer cladding region.

It is further preferred that the inner cladding features have a diameter that is smaller than a diameter of the outer cladding features. This provides a relatively easy design to allow realization of raised cladding micro-structured fibres.

In a further preferred embodiment, the refractive index of the core material is lower than the refractive index of the inner cladding region material. This allows a simple design for a fibre exhibiting a shifting wavelength.

A further preferred embodiment has a centre-to-centre spacing between inner and outer cladding features that is substantially identical.

In a further preferred embodiment, the refractive index of the inner cladding material is substantially identical to the refractive index of the outer cladding material.

In a further preferred embodiment, the filling fraction of inner cladding features in the inner cladding region is smaller than the filing fraction of outer cladding features in the outer cladding region.

In a further preferred embodiment, the refractive index of the inner cladding material is larger than the refractive index of the outer cladding material and the inner cladding features in the cross-section occupy an area, $F_i$, of the inner cladding region and the outer cladding features in the cross-section occupy an area, $F_o$, of the outer cladding region, and $F_i$ is equal to or larger than $F_o$.

In a further preferred embodiment, the core region comprises a multitude of spaced apart core features. This allows an even higher flexibility for tuning the dispersion properties – as discussed in the first aspect of this invention.

In a further preferred embodiment, the refractive index of the core material is substantially identical to the refractive index of the inner cladding region material.

In a further preferred embodiment, the refractive index of the core material is substantially identical to the refractive index of the outer cladding region material.

In a further preferred embodiment, the core features have a diameter that is smaller than the diameter of the inner cladding features.

In a further preferred embodiment, the core features have a centre-to-centre spacing that is smaller than the centre-to-centre spacing of the inner cladding features.

In a further preferred embodiment, the outer cladding features occupy more than 30% of the cross-section of the outer cladding region, such as more than 40%, such as more than 50%, such as more than 60%, such as more than 70%, such as more than 80%.

In a further preferred embodiment, the inner and/or outer cladding features are periodically disposed.

In a further preferred embodiment, the core features are periodical core features.

In a further preferred embodiment, the core has a diameter larger than 2 μm.

In a further preferred embodiment, the core diameter is in the interval from 2 to 10 μm, such as in the interval from 4 to 6 μm.

In a further preferred embodiment, the inner and/or outer cladding features have a spacing in the range of about 0.1 to 10 times the wavelength of any light guided through the fibre, such as in the range of about 0.5 to 1, such as in the range of about 1 to 2, such as in the range of about 2 to 5, such as in the range of about 5 to 10.

In a further preferred embodiment, the core features have a spacing in the range of about 0.1 to 10 times the wavelength of any light guided through the fibre, such as in the range of about 0.5 to 1, such as in the range of about 1 to 2, such as in the range of about 2 to 5, such as in the range of about 5 to 10.

In a further preferred embodiment, the core features have a spacing in the range of about 0.1 μm to 10 μm, such as in the range of about 0.5 μm to 1 μm, such as in the range of about 1 μm to 2 μm, such as in the range of about 2 μm to 5 μm, such as in the range of about 5 μm to 10 μm.

In a further preferred embodiment, any of the core features and/or any of the inner or the cladding features are voids.

In a further preferred embodiment, the core features and/or the cladding features are voids containing air, another gas, or a vacuum.

In a further preferred embodiment, any of the core features and/or the cladding features are voids containing polymer(s), a material providing an increased third-order non-linearity, a photo-sensitive material, or a rare earth material.

In a further preferred embodiment, the fibre guides light with wavelength(s) in the range from about 0.1 μm to 15 μm, such as from about 0.5 μm to 1.6 μm, such as from about 1.0 μm to 2.0 μm, such as from about 2 μm to 5 μm, such as from about 5 μm to 15 μm.

In a further preferred embodiment, the core or the cladding may comprise a dopant (e.g. an active or photosensitive material) or a material showing higher order (non-linear) optical effects.

In a further preferred embodiment, higher order (non-linear) effects may be used for e.g., soliton communication or more generally in applications, where non-linear effects are influencing the propagation properties of signals in optical communication systems. This also includes realisation of components for optical signal processing and for switching.

In a further preferred embodiment, especially for applications for fibre lasers or fibre amplifiers, the dopant in the core or the cladding may be e.g., a rare-earth dopant adapted to receive pump radiation and amplify radiation travelling in the core region.

In a further preferred embodiment, the dopant may be a light sensitive dopant, such as Germanlum. In that situation, the dopant may be use for e.g. optically writing a grating in the fibre or core region.

Brief description of the drawings:

Fig. 1 illustrates schematically the design of a typical micro-structured fibre known from the prior art.

Fig. 2 illustrates the core region of the fibre in Fig. 1.

Fig. 3 shows a scannlng electron micrograph of a real, micro-structured fibre with a design known from the prior art.

Fig. 4 shows the mode field distribution of the fundamental mode of a micro-structured fibre.

Fig. 5 shows the dispersion properties of micro-structured fibres with relatively small cladding air holes.

Fig. 6 shows the cut-off properties of a micro-structured fibre with a design known from the prior art.

Fig. 7 shows the mode field distribution of the second-order mode of a micro-structured fibre. The two lobes of the mode field have a 180 degree phase reversal between them which is indicated by the plus and minus signs.

Fig. 8 illustrates a fibre according to the present invention. The fibre has a core region containing a multiplicity of core features. The core features are smaller in size and more closely spaced than the cladding features.

Fig. 9 shows a close-up of the core region (and the inner part of the cladding region) for the fibre in Fig. 8.

Fig. 10 shows another fibre according to the present invention. The fibre has core and cladding features positioned at the same places as the fibre in Fig. 8, but the cladding features are significantly larger.

Fig. 11 illustrates a prior art fibre with a high filling fraction in the cladding. The fibre supports a high number of guided modes (only the effective index ($\beta$/k) of the fundamental and second-order mode are illustrated). The dark area indicates cladding modes. The fundamental mode displays attractive dispersion properties, but these cannot be utilized in practice since the fundamental mode will couple to the second-order mode. The fibre structure is illustrated in the right part of the figure.

Fig. 12 illustrates a fibre with micro-structured core region. The core holes introduce a suppression of both the fundamental and second-order mode (as well as for all other modes guided by the fibre – which are for reasons of clarity not illustrated). The fundamental mode still exhibit attractive dispersion properties. The second-order mode cut-off is shifted towards shorter wavelengths compared to the prior art fibre – see Fig. 11 The cladding holes are spaced further away from each other compared to the core holes, and the air filling fraction in the core region is significantly lower than in the cladding region. This effect is caused by the effective indices of the guided modes being lowered. This is caused by the core region having an effective index, which is lower than the refractive index of the core in the prior art fibre.

Fig. 13 illustrates a fibre with micro-structured core region. The core holes introduce a complete suppression of all other modes than the fundamental mode. The fundamental mode still exhibit attractive dispersion properties and the fundamental mode has a relatively large fraction of the light guided in air. This amount of light that is guided in air is roughly related to the $\beta/k$-value, where a $\beta/k$-value closer to one means a larger degree of

air guidance. The cladding holes are spaced further away from each other compared to the core holes, and the air filling fraction in the core region is lower than in the cladding region.

Fig. 14 schematically shows the dispersion properties at visible to near-infrared wavelength of the fibre in Fig 13.

Fig. 15 illustrates schematically the operation of dispersion compensating fibres known from the prior art.

Fig. 16 illustrates schematically the operation of dispersion compensating fibres disclosed in this application.

Fig. 17 shows a fibre according to the present invention. The fibre has a solid core that has a lower refractive index than the refractive index of the background cladding material and a raised, micro-structured, inner cladding region.

Fig. 18 illustrates schematically the operation of dispersion compensating fibres disclosed in this application.

Fig. 19 shows a further example of a fibre according to the present invention. The fibre has a raised, micro-structured, inner cladding region.

Fig. 20 shows yet another example of a fibre according to the present invention. The fibre has micro-structured core region and a raised, micro-structured, inner cladding region.

Fig. 21 illustrates the operation of the Fibre in Fig. 20 through the use of effective refractive index considerations.

Fig. 22 shows a simplified illustration of the operation of the fibre in Fig. 20.

Fig. 23 shows the dispersion properties of a fibre according to the present invention. The dispersion at near-infrared wavelengths is lower than –4000 ps/km/nm.

Fig. 24 shows yet another example of a fibre design according to the present invention.

Fig. 25 shows yet another example of a fibre design according to the present invention.

Detailed description of the invention and some preferred embodiments:

A typical micro-structured fibre known from the prior art is illustrated schematically in Fig. 1. The figure shows a cross-section of the fibre. The fibre consists of a background material (10) and it is invariant in the longitudinal direction (the direction perpendicular to the illustrated cross-section) and it has a cladding region characterized by an array of features (11) running along the fibre axis. In the prior art, the most commonly used background material is silica and the features are most commonly air holes. The holes are in this case arranged periodically (in a so-called close-packed or triangular arrangement), but the holes may also be non-periodically or randomly distributed (see e.g. Monro-reference). In the centre of the fibre (12) a single hole has been left out in order to form a high-index core region. In Fig. 2, the core region is schematically illustrated (20) along with the centre-to-centre distance between two nearest air holes, $\Lambda$. In the case of micro-structured fibres with periodically arranged holes, these form in the cross-section a two-dimensionally periodic lattice with a lattice constant equal to $\Lambda$.

Micro-structured fibres are commonly fabricated using a relatively simple procedure, where an array of silica rods and tubes are stacked by hand to form a preform, that may be drawn into fibre using a conventional tower setup. Various lattice structures may be realized using this technique by positioning rods and tubes during the stacking process in a close-packed arrangement. Such preforms are readily drawn to dimensions, where centre-to-centre spacing between two nearest air holes may be less than 2.0 µm, while preserving the initial air hole lattice in the cross-section of the fibres. Fig. 3 shows an example of a final micro-structured fibre - with a regular air hole arrangement - that has been realized using a so-called stack-and-draw process. The fibre in Fig. 3 has air holes arranged in a triangular lattice, and a high-index core is formed by the omission of a single air hole. Light may be guided efficiently in the core region of micro-structured fibres, and an example of the fundamental mode that is guided in micro-structured fibre known from the prior art is illustrated in Fig. 4.

Fig. 5 shows the dispersion properties at near-infrared wavelengths of a series of typical micro-structured fibres known from the prior art. The fibres have all a design as shown in Fig. 1, but the cladding air holes are varied from $d/\Lambda$= 0.10 to 0.45. The simulation of the

fibres is for a fixed $\Lambda$ value of 2.3 μm. The dispersion properties are simulated using a full-vectorial mode-solver as a function of wavelength. From the figure, it is first noted that for very small air hole sizes, e.g., when the influence of the air holes is strongly limited, the dispersion curve is very close to the material dispersion of pure silica (zero dispersion wavelength around 1.3 μm). As the diameter of the air holes is increased, the waveguide dispersion becomes increasingly strong. This shows that the waveguide dispersion may be positive at wavelengths below 1.3 μm, while the fibres simulated in Fig. 5 are all single-mode due to the relatively small size of the cladding holes ($d/\Lambda$ equal to or less than 0.45). These dispersion properties are well known for micro-structured fibres, but are unattainable for conventional optical fibres. Such dispersion properties may be utilized in applications such as white-light and soliton generators.

The air-filling fraction is a key parameter to increase in order to further increase the dispersion of micro-structured fibres. This may be desired in order to shift the zero-dispersion to even shorter wavelengths than presently possible, or to allow the use of shorter fibre length for obtaining a given dispersion effect. It is, however, well known from the prior art that micro-structured fibres may become multi-mode for large cladding air-filling fractions – and that the largest possible cladding air hole size that can be employed in order for the prior art fibres to be strictly single-mode at all wavelengths is about $d/\Lambda=0.45$ (see e.g. Birks et al, Optical Fiber Communication Conference, paper. FG4-1, 1999.).

The cut-off properties of prior art micro-structured fibres may be understood from Fig. 6, which shows the effective index of the guided modes of a micro-structured fibre with relatively large air holes in the cladding region. The cladding air holes are identical and they have a size $d/\Lambda=0.6$, where $d$ is the air hole diameter, and $\Lambda$ is the centre-to-centre spacing of two nearest air holes. The figure shows additionally the effective refractive indices of the core region and the cladding region. The core region is made of pure silica and it is, therefore, equal to 1.45 (which is a representative value for silica at visible to near-infrared wavelengths). The cladding region on the other hand contains air holes which act to lower the effective refractive index significantly below the index of the core region. The fibre supports at least two modes and the mode-field distribution of the second-order mode is illustrated in Fig. 7. The second-order mode has a mode cut-off wavelength of $\Lambda/1.5$. Hence, to avoid the second-order mode at e.g. a wavelength of 632nm, the centre-to-centre hole spacing, $\Lambda$, must be scaled to less than 1 μm. For the

specific fibre in Fig. 4, this gives a core diameter of less than 2 μm (the core diameter may be approximated by two times Λ for the specific design).

In contrast to the fibre of the prior art, the present inventors have realised how to increased the features significantly above $d/\Lambda=0.45$ (and thereby obtain the desired dispersion properties this gives access to) while keeping the fibres substantially single-mode at all wavelengths. This is obtained by applying into the core region elongated features with a size that is smaller than the size of the cladding features, while at the same time the core feature spacing is smaller than the cladding feature spacing. Hereby, the present inventors have realised that the cut-off wavelength of any higher order modes may be pushed to very short wavelength – and for certain fibre dimension the second-order mode cut-off may be completely eliminated even for fibres with large features in the cladding. Figure 8 shows schematically a fibre according to the present invention, which has a background material (80) containing cladding features (81) of diameter, $d_{cl}$, and spacing, $\Lambda_{cl}$, and a core region (82) that contains (in this case) seven core features (83). A close-up of the core region is schematically illustrated in Fig. 9, where the core feature diameter, $d_1$, and the core feature centre-to-centre spacing, $\Lambda_1$, is illustrated. The fibre in Fig. 8 and 9 is characterized by $d_{cl}>d_1$ and $\Lambda_{cl}>\Lambda_1$. While the Figures 8 and 9, show a fibre according to the invention with medium sized cladding features, fibres with even larger cladding features ($d_{cl}/\Lambda_{cl}$ larger than 0.6) will be further advantageous when core features are provided. Fig. 10 shows a schematic example of a fibre according to the present invention with large cladding features (100) and smaller features (101) in the core region.

To illustrate the findings of the present inventors, the figures 11 to 13 documents how it is possible to eliminate the second-order mode (as well as any higher-order modes) by introducing features into the core region of a fibre with very large cladding features. In the specific example, the fibre consists of pure silica with features made of air. The cladding features have in the specific example a size of $d/\Lambda=0.9$. However, also for smaller cladding features it will be advantageous to introduce features into the core region. Fig. 11 illustrates the operation of fibre with a solid core (a fibre design that is known from the prior art). The figure shows the relation between propagation constant along the fibre axis, $\beta$, and free space wavenumber, $k$, for modes in the fibre. The propagation constant is normalized with respect to the cladding feature spacing, Λ. The fibre supports a multitude of guided modes, but only the two lowest order modes have been shown for reasons of clarity (the fundamental mode has the highest $\beta/k$ value for a given $\beta$ value). The semi-

infinite, dark region (the region below the line corresponding to the effective refractive index of the cladding) illustrates the continuum of cladding modes existing in the fibre. In this region the fibre cannot guide light efficiently along its length in the fibre core. The right side of the figure illustrates schematically the fibre morphology, where full lines illustrate the air holes. By introducing small features into the core region, the guided modes may be slightly pushed towards the dark region (the non-guiding region). This behaviour is illustrated in Fig. 12. If the core features are further increased in size, but still obeying the conditions that they should be smaller and more closely spaced than the cladding features, then the second-order mode may be completely eliminated. This behaviour is illustrated in Fig. 13. The advantageous of the type of fibre shown in Fig. 13 is that a strong dispersion can be obtained (a result of the large cladding features) while the fibre is strictly single mode. This can be used to shift the zero dispersion wavelength significantly below 1.3 μm, while maintaining single mode operation. Furthermore, the type of fibre shown in Fig. 13 will have a larger core size than a fibre with similar sized cladding elements that has to obey the requirement of single mode operation. For the fibre shown in Fig. 13, the core size may be larger than 2 μm in diameter and operate with large dispersion at visible wavelengths. In fact the core diameter may easily be designed to be in the interval from 2 to 10 μm for the type of fibre illustrated in Fig. 13. Core sizes within this interval are of importance for a range of specific applications, where a high coupling coefficient between micro-structured fibres and conventional fibres are required. As a further mean to improve the coupling to conventional fibres, it is desired to shape the mode field using a high number of core features.

The fibres disclosed in this application have a micro-structured core region surrounded by a micro-structured cladding region. The core region should also in this respect preferably consist of more than 2 features in order to provide a significant variation of the effective refractive index of the core region as a function of wavelength.
The dispersion properties of the fibre shown in Fig. 13 are simulated and presented in Fig. 14.

While the present inventors have realized that micro-structured fibres may be significantly improved by introducing a specifically designed micro-structure in the core region, it is important to notice that the micro-structured cores only for certain wavelength ranges have an effective refractive index that is higher than the cladding region(s). Hence, the fibres will only over a limited wavelength range guide light in the core by TIR. This is seen

in Fig. 13 where a cut-off value exists for the fundamental mode. The fibres may, however, also guide light outside the wavelength ranges where TIR takes place. This can result from waveguidance by PBG effects, a waveguidance mechanism that can also be utilized in the fibres covered by the present invention. This requires, however, that the cladding region has a periodic distribution of the cladding features. Such a requirement is not necessary for the majority of fibres disclosed in this application which may well have non-periodically distributed cladding features (and guide light by TIR).

As documented by the discussion above, the effective index of the core micro-structure may for certain wavelength regions be strongly wavelength dependent for fibres according to the present invention. This may provide the fibres with a relatively low core-cladding effective refractive index difference even for large cladding features. The low core-cladding effective refractive index difference represents the key issue that allows to suppress the second-order mode cut-off completely or to shift it to wavelengths shorter than a desired operational wavelength. Hereby the strong dispersion of the fundamental mode can be achieved in the micro-structured fibres while being under single-mode operation. According to the present invention, it will be further advantageous, if the refractive index of the core background material is lower than that of the background cladding material (e.g. if the fibre is made of silica glass, that the silica core material is doped so that is has a lower refractive index than the cladding background material). This will act to further suppress the second-order mode cut-off. As already mentioned then it should be noticed that the fibres, disclosed in this application, may be characterized by a cut-off wavelength for the fundamental mode, in which case the fibres will not transmit light at wavelengths shorter than a certain critical value. This cut-off wavelength may, however, be designed to be shorter than a desired operational wavelength. A further embodiment of the present invention includes micro-structured fibres with a core region, which is characterized by a microstructure having a different microstructure than the cladding region and where the effective index of the core region is higher than the effective index of the cladding at long wavelengths and becomes lower at wavelengths shorter than a certain critical value. This requires a core region where the background material has been doped to a lower nominal value than the background material of the cladding mlcrostructure and/or the core microstructure has a lower filling fraction than the cladding microstructure. It is important to notice that both the core and cladding microstructures may be substantially periodic or they may be non-periodic. The core structure may, in principle, be periodically micro-structured without paying respect to

whether the cladding structure is periodically micro-structured, and vice versa. The advantage of the latter type of embodiment is that a more circular symmetric mode field distribution in the fibre cross-section may be obtained at a desired wavelength. This type of embodiment may, however, not provide a complete suppression of the second-order mode. A further way of providing a smoothing of the mode field is by providing additional elements (either ring-shape features surrounding completely the core region or discrete elements such as air holes in a ring around the core centre) in close proximity to the core-cladding interface.

In a preferred embodiment, the cladding has features of size $d/\Lambda$ larger than 0.45 – and the core region contains more than one elongated feature (usually voids in the form of air holes). Preferably the number of core features is larger than 2 in order to utilize the core features to shape the guided mode of the fibre to a desired profile. Using just a single hole will either provide a single, centrally air hole – causing an undesired mode profile with a low coupling coefficient with respect to Gaussian mode profiles (that is the profile of conventional fibre) or cause an a-symmetric profile. Hence with the aid of two or more holes, the guided mode(s) may be shaped to more desired profiles, while at the same time serving to push the second-order mode cut-off to short wavelengths. Furthermore, it is preferred that the number of significantly higher than 2, such as higher than 5 or higher than 17 and that the spacing between core features becomes very small (much smaller than the wavelength of light guided through the fibre). By this, the light will not be able to avoid the core features, and a large fraction of the light may, consequently, be guided within the features. In a further preferred embodiment, the features are voids containing air, a purified gas or vacuum, hence allowing a fibre to guide with low losses.

Apart from the potential of strongly shifting the zero-dispersion wavelength, Fig. 5 also shows a near-zero, broadband dispersion flattened behaviour of crystal fibres with $d_c/\Lambda$ around 0.30. Due to the exhibition of positive waveguide dispersion at short wavelengths, the dispersion-flattened range is in fact extended to wavelengths below 1.3 µm down to approximately 1.1 µm. The attractive potential for micro-structured fibres of finding use as a standard transmission fibre in broadband optical communication seem, therefore, with respect to the dispersion properties, possible to fulfil. The large tailorability in the design of the crystal fibres, with respect to air holes sizes, shapes and arrangements provides a further fruitful mean of tuning of the dispersion curve to obtain specific properties. Micro-

structuring of the core as disclosed in this application provides further flexibility for designing fibres with flat, near-zero dispersion over broad wavelength ranges.

Yet another aspect of micro-structured fibres is their ability to provide dispersion compensation at near-infrared wavelengths – and at 1.55 μm in particular. The present inventors have realised how to provide a significantly higher degree of freedom for tailoring the negative dispersion of micro-structured fibres compared to both traditional fibres and previously known micro-structured fibres. The present inventors have realised a design-route for such micro-structured fibres, and the present invention discloses a number of specific design of micro-structured fibres with large negative dispersion.

The fibres are characterized by a number of elongated cladding elements surrounding a core region – and the cladding elements are designed in such a way that the field distribution of light guided through the fibre will be much more wavelength dependent compared to any previously known fibre. This strong wavelength dependence provides the means for creating optical fibres with extremely strong dispersion. The present invention, therefore, includes designs of novel types of dispersion manipulating optical fibres that are able to compensate - over a small fibre length - the dispersion of conventional optical fibres that are already installed in many telecommunication systems. Hence, fibres according to the present invention may be utilized as short dispersion compensating components that can be inserted into existing systems.

Conventional optical fibres may be designed to exhibit normal dispersion. Such fibres are widely used on a commercial basis to provide dispersion compensation in optical fibres systems that are upgraded from operation at wavelength around 1.3 μm to operation at wavelengths around 1.55 μm. These dispersion-compensating fibres allow us primarily to significantly increase the transmission capacity over an existing fibre optical communication system. The dispersion compensating conventional optical fibres is commonly characterized by a so-called depressed cladding – an inner cladding region that has a lower refractive index than the core and an outer cladding region. Multiple depressed cladding designs are also well known from conventional optical fibres. Also micro-structured fibres have been designed for dispersion compensating purposes with a depressed, micro-structured, inner cladding region (see e.g. US patent no. 5,802,236). Both the conventional, dispersion compensating optical fibres, and the micro-structured fibres in the above-cited reference have an operation that is illustrated schematically in Fig. 15. The figure shows the effective indices (which in the case that one (or more) of the

three illustrated fibre regions is homogeneous is identical to the conventional refractive index of that region(s)). The figure illustrates that the core at all wavelengths have the higher index, while the depressed, inner cladding region has the lowest. The outer cladding region has an index higher than the depressed cladding, but lower than the core at all wavelengths. The present inventors have, however, realised that it is not optimum to have the above-described relation between the fibre regions for all wavelengths. In contrast, the present inventors have realized that it is advantageous to have fibres where the relation between the effective refractive indices of the fibre regions is varying as illustrated in Fig. 16.

This application discloses fibres where the effective refractive index of the core may be larger than the effective indices of both an inner and outer cladding region at long wavelengths, the core index may be equal to the inner cladding index at a specific wavelength, named the shifting wavelength, but remain larger compared to the outer cladding at this wavelength, and finally, the core index may be lower than both the inner and outer cladding indices at short wavelengths. The effective index of the inner cladding region will at all wavelengths be higher than that of the outer cladding index, and we are, therefore, naming inner cladding regions, according to the invention as raised claddings. The present inventors have realized that a very strong dispersion can be obtained around the shifting wavelength, and that this shifting wavelength can be designed to any desired absolute wavelength for a number of the fibres disclosed in this application. The above-described effect may e.g. be obtained by realizing a fibre as shown in Fig. 17. The fibre has a raised, inner cladding containing the features (170), and a solid core (171) that has a lower refractive index than the background material of the fibre (172). The outer cladding region contains larger features (173) than the features of the inner cladding region.

Another example of the effective index variation of a fibre according to the invention is shown in Fig. 18. In this example, we describe fibres, where the effective refractive index of the core may be larger than the effective indices of both an inner and outer cladding region at long wavelengths. In agreement with the previously described example, the core index may be equal to the inner cladding index at a specific wavelength, named the shifting wavelength. However, in contrast to the previous example, this may be obtained for a case, where the refractive index of the background material of the inner cladding region is higher than that of the outer cladding region, provided that the air-filling fraction

of the inner cladding region Is equal to or larger than that of the outer cladding. In this example, the effective refractive index of the core may be equal to the outer cladding index at short wavelengths, but the core index may also be smaller than that of the outer cladding. Also in this case, a very strong dispersion can be obtained around the shifting wavelength, and this shifting wavelength can be designed to any desired absolute wavelength for a number of the fibres disclosed in this application.

According the invention, also a fibre with a design as illustrated in Fig. 19 will be advantageous. The fibre has smaller inner cladding features distributed in a near-ring shaped region around the core.

According to the invention, it will be further advantageous to have obtained the behaviour illustrated in Fig. 16 by introducing a micro-structure into the fibre core region. The following text is a more detailed description of a more advanced design according to the present invention, and how a large negative dispersion can be obtained. The description exemplifies the design-route that the present inventors have found in order to realize micro-structured fibres that exhibit strong dispersion.

The basic transverse structural form of the micro-structured fibres, employed to obtain a large degree of dispersion compensation (The group velocity dispersion, GVD, is very negative), is shown in Fig. 20. This is not a structure actually calculated upon in the following, however, it describes the structural idea.

In the centre is a closed-packed core-region (this means that the air-holes are situated on a triangular lattice). This implies that an air hole is situated in the central part of the core-region, which is an unusual quality in fibres, which guide light by modified Total Internal Reflection (TIR).

<u>Lattice-constants:</u> Outside the close-packed core-region is the inner cladding region. This inner cladding region is also closed-packed but the distance between the air holes (the lattice-constant, $\Lambda$) is significantly larger than the lattice-constant in the central core region. In the calculated example, as well as the structural example shown hereunder, the lattice-constant is three times as large in the inner cladding region as it is in the central core-region.

Surrounding the inner cladding region is the outer cladding region. In the calculated example (as well as the structural example shown hereunder), the inner and the outer cladding regions have the same lattice-constant. However, in the outer cladding structure, small interstitial holes are placed. The effect of these holes is that the outer cladding region behaves as if its lattice constant is slightly smaller, than the lattice constant of the inner cladding region.

The effects creating the possibility of large dispersion compensation: To explain the way this fibre works, we will use the mode-index plot, shown in Fig. 21. Here is shown the effective index of some different periodic structures. The effective index is defined in the invariant length direction, for the fundamental mode, and is defined as the wave-vectors component in the length direction (the propagation constant $\beta$), divided by the free-space wavenumber, k. For a bounded mode (exemplified by 'core-mode in the plot), this definition is compatible with the definition known from standard optical fibres. The effective index is shown as a function of the normalized wavelength, $\lambda/\Lambda$, where $\lambda$ is the free-space wavelength, while $\Lambda$ is the aforementioned lattice-constant in the inner cladding (or the outer cladding, since they are equal).

The effective index of the outer cladding is termed 'outer cladding' in the plot. The effective index of the the curve 'inner core' is similar to the effective index of the central core, since 'inner core' shows the effective index of a periodic material, identical to the central core, except that 'inner core' extends infinitely in space.

To obtain the desired effect, it is necessary to have an index of the central core (inner core) which lies above the index of the outer cladding at long (normalized) wavelengths. This is ensured by having an air-filling fraction in the central core, which is less than the air-filling fraction in the outer cladding. In the example calculated upon in this section, the central core has air-holes with a diameter of 70% of its lattice constant, while the outer cladding has air-holes with a diameter of 75% of its lattice constant. Furthermore, the outer cladding has interstitial air-holes with a diameter of 13% of the local lattice constant, which lowers the effective index of the outer cladding further at long wavelengths, compared to the effective index of the central core.

At shorter wavelengths ($\lambda/\Lambda \cong 0.79$) the effective index of the outer cladding has risen to the same level as the effective index of the central core-region. The reason behind the

significant rising of the effective index of the outer cladding, at wavelengths which are sufficiently long to ensure that the effective index of the central core-region is still fairly constant is the significantly larger lattice constant of the outer cladding compared to the central core-region. At these wavelengths the large air holes of the outer cladding have a size comparable to the wavelength, which causes the field to avoid the air-holes, which again causes the effective index to rise.

A hypothetical structure, consisting of the central core, surrounded by the outer cladding, would therefore guide light in the core-region at long wavelengths (where the effective index of the core is higher than the effective index of the cladding). At short wavelengths the fibre would become an anti-guide (not guiding in the core-region), since the effective index of the cladding has risen above the effective index of the core. On the mode-index curve shown above, one may actually see that the mode-index curve is tending towards the effective outer cladding index ($\lambda/\Lambda \cong 0.85$), due to the small index contrast between the central core and the outer cladding at these wavelengths.

However, in the structure calculated upon in the above plot, the effective index of the inner cladding rises above the effective index of the outer cladding at these wavelengths. By designing correctly, one may now obtain the following situation: Before the mode-index reaches the effective index of the outer cladding, it begins to de-localize, because of an insufficient index difference between core and cladding. However, because of the inner cladding surrounding the central core, the field is de-localizing into the inner cladding, since this inner cladding has a significantly higher index than the outer cladding at these wavelengths. Actually, this index difference is sufficiently large, for the inner cladding to guide the light.

Instead of having a central core mode, and an inner cladding mode, we obtain that the central core-mode is de-localized out into the inner cladding over a quite short wavelength interval. However, the slope of the central core-mode and the inner cladding mode is quite different, due to the large difference in structural size between the central core and the inner cladding. The guided mode-index therefore turns sharply in the wavelength region where the transition from the central core to the inner cladding (which becomes the new core) takes place.

In Fig. 22 is depicted the same calculation, except that we have zoomed in on the interesting transition region. Also, we do not show an effective index of the central core-region, and an effective index of the inner cladding. The core-index instead shows the effective index of the one of the two, which has the higher effective index at the particular wavelength. Shown like this the effective core-index appears to break at the shifting wavelength, which of course is a mathematical abstraction. Nevertheless, it explains the dramatic effect on the slope of the guided mode, since this mode is forced to have an effective index, which lies between the effective index of the cladding and the core.

The group velocity dispersion, GVD, for a guided mode can be written as:

$$GVD= -\lambda/c \, d^2n/d\lambda^2$$

From this formula, those skilled in the art will recognize that the sharp upward bending of the guided mode corresponds to a numerically large negative group velocity dispersion. The calculated group velocity dispersion of the fibre is shown in Fig. 23.

Since it has been assumed that a group velocity dispersion below –2500 ps/nm/km was unattainable in pure silica fibres at 1.5μm wavelength the numbers speak for themselves. The lattice constant in the cladding is 1.78μm, while the core-diameter is estimated to be approximately 5μm.

Another example of a fibre design according to the present invention is illustrated in Fig. 24. The fibre consists of a core-region with relatively small air holes. Surrounding the core-region is an inner cladding region that has a higher percentage of air than the core region (ensuring that the core has a higher effective index than the inner cladding at long wavelengths. The inner cladding structure further has a significantly larger structure scale than the core-region ensuring that the effective index of the inner cladding becomes equal to the effective index of the core-region at the shifting wavelength (the longest free-space wavelength where the effective index of the core-region is equal to the effective index of the inner cladding). At shorter free space wavelengths than the shifting wavelengths the effective index of the inner cladding raises above the effective index of the core-region.

The reason that the index of the inner cladding region raises above the effective index of the core region is that the air holes of the inner cladding are avoided by the field at much

longer wavelengths than the air holes of the core-region. This is due to the larger structural size of the inner cladding.

Surrounding the inner cladding is the outer cladding, which has the same structural size as the inner cladding. However, the air-filling fraction of the outer cladding is greater than the air-filling fraction of the inner core, since the air holes are largest in the outer cladding. The effective index of the outer cladding is therefore lower than the effective index of the inner cladding at all wavelengths. The effective index of the three distinct parts of the fibre therefore behaves in accordance with the preferred behaviour shown in Fig. 16. Fig. 24 is therefore an example of a preferred embodiment where the desired behaviour is obtained by having different structural sizes in different parts of the fibre.

The different patterns in the background of the different parts of the structures, exemplifies that the behaviour may be further refined by employing different background materials in the fibre. By using different background index in one of the regions of the fibre, it becomes possible to obtain a more desirable combination of the effective index and the slope of the effective index in the working wavelength range of the fibre. This allows more flexibility when tailoring the dispersion of the fibre.

Fig. 25 shows yet another preferred way to obtain a different structural size in different regions of the fibre. Here the typical minimum inter-hole distance is equal in all three parts of the fibre. The core-region has air holes on a triangular lattice and the inner cladding has air holes on a honeycomb lattice. The outer cladding has relatively large air holes on a honeycomb lattice and relatively small air holes in the centres of the honeycombs (on a larger triangular lattice). Even though the typical inter-hole spacing is equal in all parts of the fibre, the typical structural size is much smaller in the core-region compared to the cladding regions. It is therefore possible to obtain effects similar to those found in the structure shown in Fig. 24, using this embodiment.

Again it is illustrated how different parts of the fibre can have different refractive indices of their background material, allowing more flexibility in the design of the fibre. One possible advantage of the design shown in Fig. 25, compared to the other structures shown, is that it becomes possible to have an effective index of the core-region, which is comparable to the effective index of the outer cladding, even at short wavelengths. This makes it easier to keep the fibre single-moded even at short wavelengths.

Those skilled in the art will recognise, that a multitude of structures exist, which has different structural sizes in different parts of the fibre. These structures include: holes on a triangular lattice (as in the core-regions shown in Fig. 24-25), holes on a honeycomb lattice (as the inner cladding shown in Fig. 25), holes on a honeycomb and a triangular lattice (as the outer cladding shown in Fig. 25), holes on a Kagomé lattice (not shown) and holes on a Kagomé and a triangular lattice (not shown).

CLAIMS:

1. An article comprising a micro-structured optical fibre having an axial direction and a cross section perpendicular to said axial direction, the optical fibre comprising a core region that comprises a multiplicity of spaced apart core features that are elongated in the fibre axial direction and disposed in a core material, the core being surrounded by a cladding region that comprises a multiplicity of spaced apart cladding features that are elongated in the fibre axial direction and disposed in a first cladding material;

   CHARACTERIZED IN THAT

   the core features have a centre-to-centre spacing that is smaller than the centre-to-centre spacing of the cladding features.

2. An article according to claim 1, wherein the core has a diameter larger than 2 μm.
3. An article according to claim 2, wherein the core has a diameter in the range of about 2 μm to 50 μm, such as in the range from about 2 μm to 5 μm, such as from about 5 μm to 10 μm, such as from about 10 μm to 25 μm, such as from about 25 μm to 50 μm.
4. An article according to claim 1 or 2, wherein the cladding features have a diameter that is larger than 0.45 times the cladding feature spacing, such as a diameter larger than 0.6 times the cladding feature spacing, such as larger than 0.9 times the cladding feature spacing.
5. An article according to claim 3, wherein cladding features occupy at least 25% of the cross-section of the cladding region, such as more than 40%, such as more than 50%, such as more than 60%, such as more than 70%, such as more than 80%.

6. An article according to any of the preceding claims, wherein the core features occupy more than 5% of the cross-section of the core region, such as more than 10%, such as more than 25%, such as more than 50%, such as more than 75%.

7. An article according to any of the preceding claims, wherein the cladding features are periodical cladding features.

8. Article according to claim 1, wherein the number of core features is larger than 2, such as larger than 5, such as larger than 17.

9. An article according to any of the preceding claims, wherein the core features are periodical core features.

10. An article according to any of the preceding claims, wherein the spacing of the core features and of the cladding features are in the range of about 0.2 μm to 50 μm.

11. An article according to any of the preceding claims, wherein the core material and/or the cladding material is silica.

12. An article according to any of the preceding claims, the refractive index of the core material is lower than the refractive index of the first cladding material.

13. An article according to any of the preceding claims, wherein the core features and/or the cladding features are voids.

14. An article according to any of the preceding claims, wherein the core features and/or the cladding features are voids containing air, another gas, or a vacuum.

15. An article comprising a micro-structured fibre having an axial direction and a cross section perpendicular to said axial direction, the optical fibre comprising a core region surrounded by an inner cladding region that comprises a multiplicity of spaced apart inner cladding features that are elongated in the axlal direction and disposed in an inner cladding material, the inner cladding region being surrounded by an outer cladding region that comprises a multiplicity of spaced apart outer cladding features that are elongated in the axial direction and disposed in an outer material, the inner cladding features having a refractive index that differs from a refractive index of the inner cladding material and the inner cladding region having an effective refractive index $N_I$, and the outer cladding features having a refractive index that differs from a refractive index of the outer cladding material and the outer cladding region having an effective refractive index $N_o$;

CHARACTERIZED IN THAT

$N_I$ is larger than $N_o$.

16. An article according to claim 15, wherein the inner cladding features have a diameter that is smaller than a diameter of the outer cladding features.

17. An article according to claims 15 or 16, wherein the refractive index of the core material is lower than the refractive index of the inner cladding region material.

18. An article according to claims 15,16, or 17, wherein the centre-to-centre spacing between inner and outer cladding features is substantially identical.

19. An article according to any of the claims 15 to 18, wherein the refractive index of the inner cladding material is substantially identical to the refractive index of the outer cladding material.

20. An article according to any of the claims 15 to 19, wherein the inner cladding features in the cross-section occupy in total a ratio, $F_i$, of the inner cladding region and the outer cladding features in the cross-section occupy in total a ration, $F_o$, of the outer cladding region, and $F_i$ is smaller than $F_o$.

21. An article according to any of the claims 15 to 18, wherein the refractive index of the inner cladding material is larger than the refractive index of the outer cladding material and the inner cladding features in the cross-section occupy an area, $F_i$, of the inner cladding region and the outer cladding features in the cross-section occupy an area, $F_o$, of the outer cladding region, and $F_i$ is equal to or larger than $F_o$.

22. An article according to any of the claims 15 to 21, wherein the core region comprises a multitude of spaced apart core features.

23. An article according to claim 22, wherein the refractive index of the core material is substantially identical to the refractive index of the inner cladding region material.

24. An article according to any of the claims 15 to 23, wherein the refractive index of the core material is substantially identical to the refractive index of the outer cladding region material.

25. An article according to any of the claims 15 to 24, wherein the core features have a diameter that is smaller than the diameter of the inner cladding features.

26. An article according to any of the claims 15 to 25, wherein the core features have a centre-to-centre spacing that is smaller than the centre-to-centre spacing of the inner cladding features.

27. An article according to any of the claims 15 to 26, wherein the outer cladding features occupy more than 30% of the cross-section of the outer cladding region, such as more than 40%, such as more than 50%, such as more than 60%, such as more than 70%, such as more than 80%.

28. An article according to any of the claims 15 to 27, wherein the inner and/or outer cladding features are periodically disposed.
29. An article according to any of the claims 15 to 28, wherein the core features are periodical core features.
30. An article according to any of the claims 15 to 29, wherein the core has a diameter larger than 2 μm.
31. An article according to claim 23, wherein the core diameter is in the interval from 2 to 10 μm, such as in the interval from 4 to 6 μm.
32. An article according to any of the claims 15 to 31, wherein the inner and/or outer cladding features have a spacing in the range of about 0.1 to 10 times the wavelength of any light guided through the fibre, such as in the range of about 0.5 to 1, such as in the range of about 1 to 2, such as in the range of about 2 to 5, such as in the range of about 5 to 10.
33. An article according to claim 30, wherein the core features have a spacing in the range of about 0.1 to 10 times the wavelength of any light guided through the fibre, such as in the range of about 0.5 to 1, such as in the range of about 1 to 2, such as in the range of about 2 to 5, such as in the range of about 5 to 10.
34. An article according to any of the claims 1 to 14 or 30 or 33, wherein the core features have a spacing in the range of about 0.1 μm to 10 μm, such as in the range of about 0.5 μm to 1 μm, such as in the range of about 1 μm to 2 μm, such as in the range of about 2 μm to 5 μm, such as in the range of about 5 μm to 10 μm.
35. An article according to any of the preceding claims, wherein any of the core features and/or any of the inner or the cladding features are voids.
36. An article according to any of the preceding claims, wherein the core features and/or the cladding features are voids containing air, another gas, or a vacuum.
37. An article according to any of the preceding claims, wherein any of the core features and/or the cladding features are voids containing polymer(s), a material providing an increased third-order non-linearity, a photo-sensitive material, or a rare earth material.
38. An article according to any of the preceding claims, wherein the fibre guides light with wavelength(s) in the range from about 0.1 μm to 15 μm, such as from about 0.5 μm to 1.6 μm, such as from about 1.0 μm to 2.0 μm, such as from about 2 μm to 5 μm, such as from about 5 μm to 15 μm.

Figures:

Fig 1

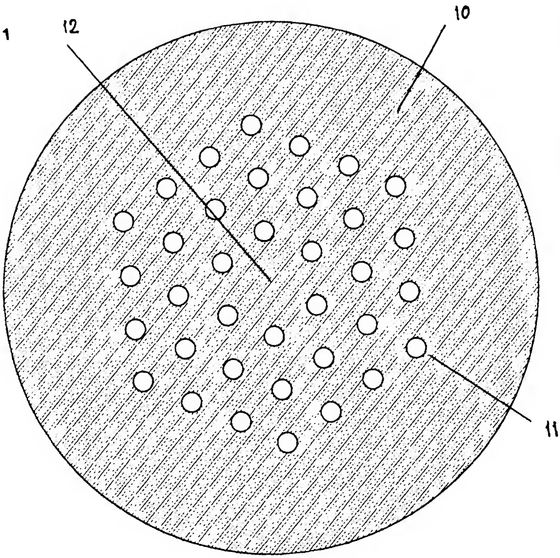

Fig. 2

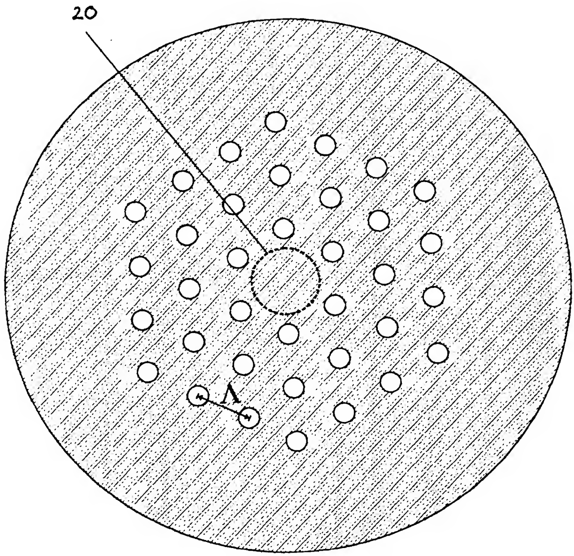

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Fig. 3

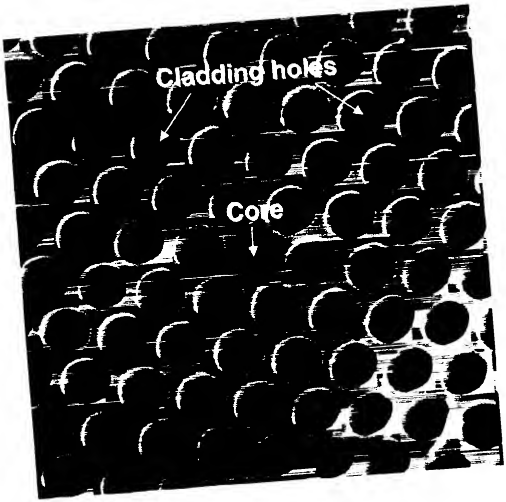

**Fig. 4**

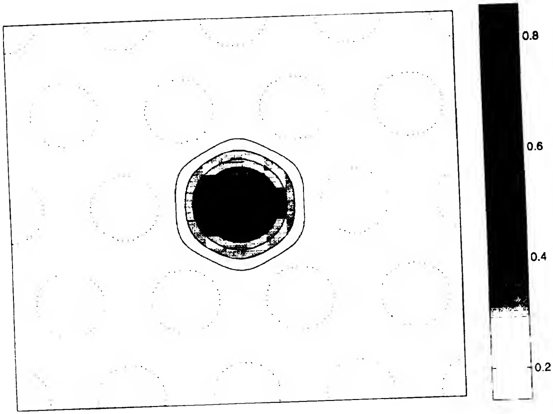

**Fig. 5**

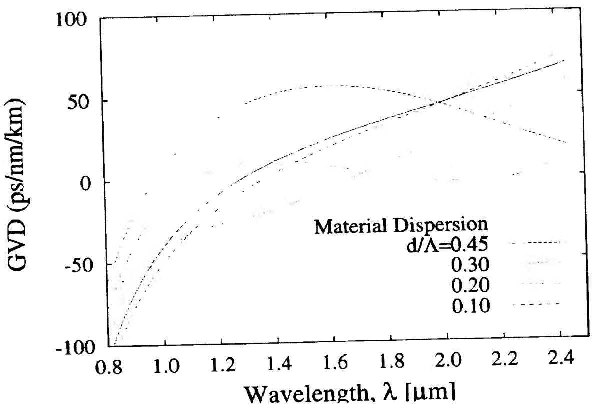
100
50
0
-50
-100
GVD (ps/nm/km)
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
Wavelength, λ [μm]
Material Dispersion
d/Λ=0.45
0.30
0.20
0.10

Fig. 6

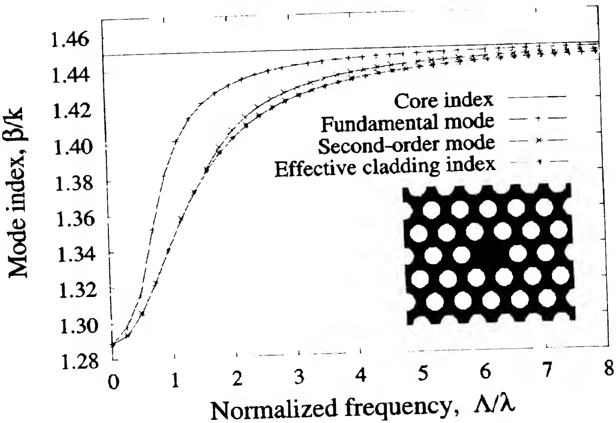
Mode index, β/k
1.46
1.44
1.42
1.40
1.38
1.36
1.34
1.32
1.30
1.28
0
1
2
3
4
5
6
7
8
Normalized frequency, Λ/λ
Core index
Fundamental mode
Second-order mode
Effective cladding index

Fig. 7

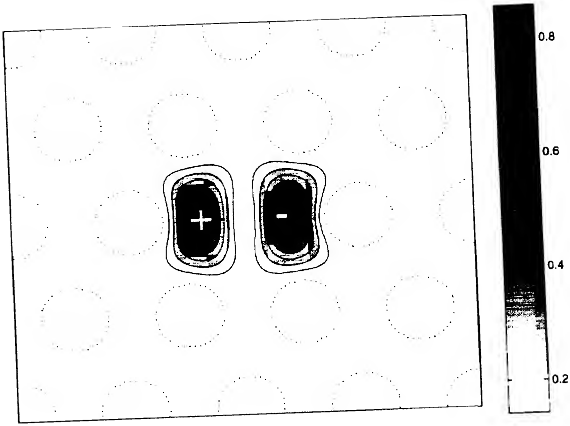

Fig. 8

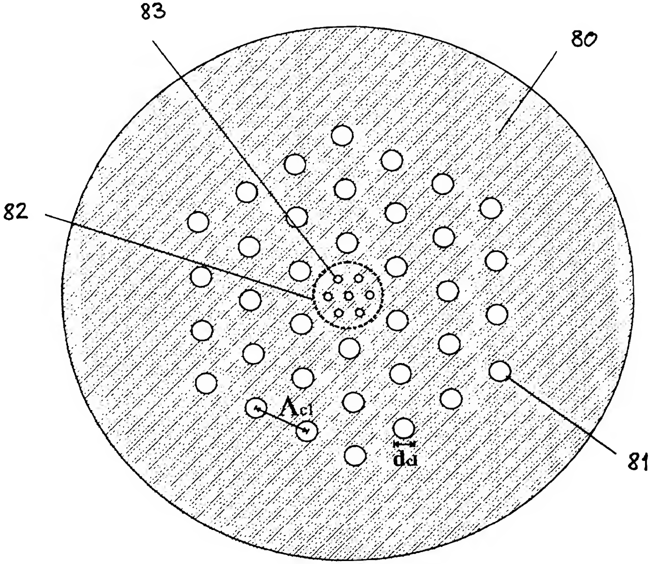

Fig. 9

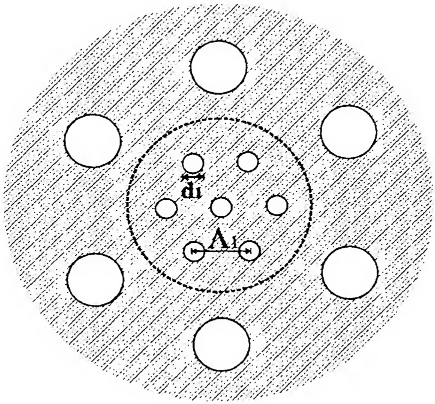

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**Fig. 10**

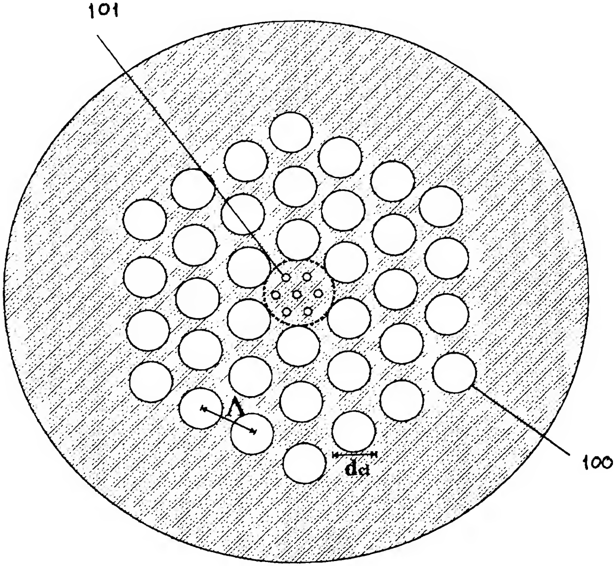
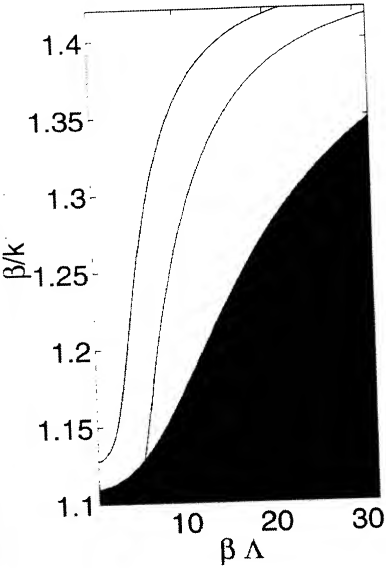


Fig. 11



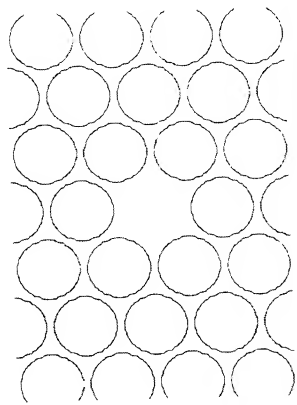



Fig. 12

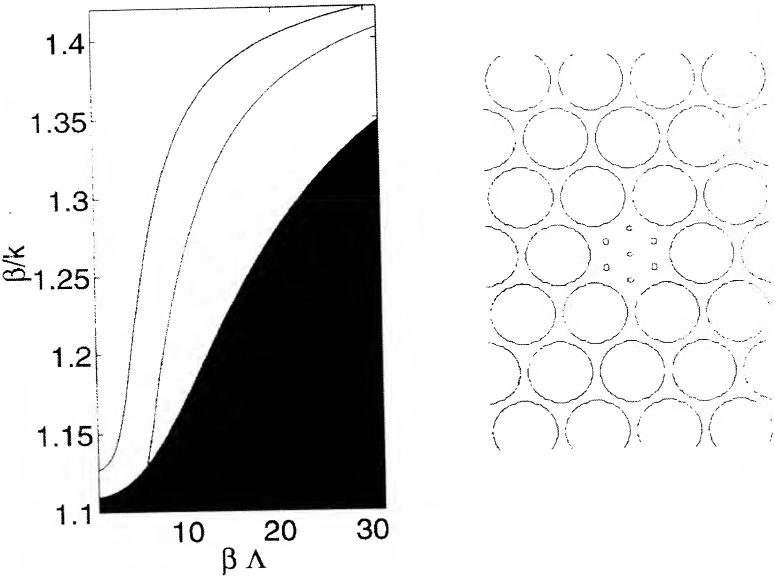


Fig. 13

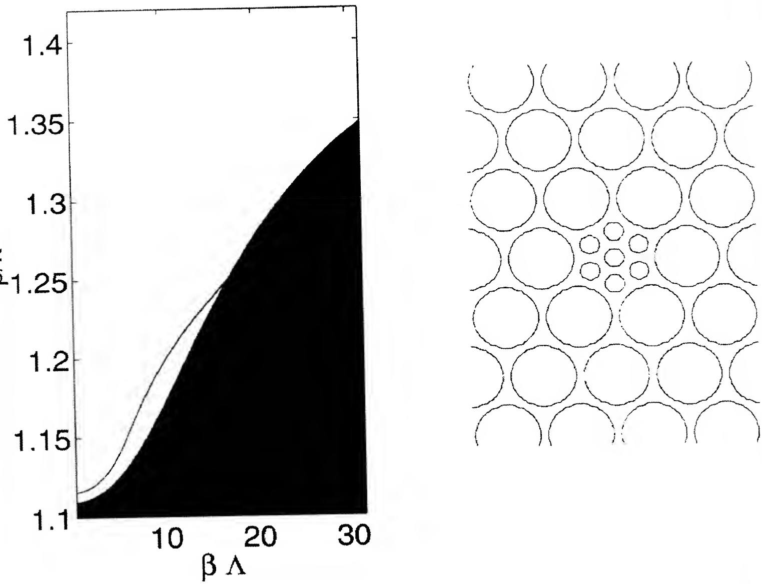


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Fig. 14

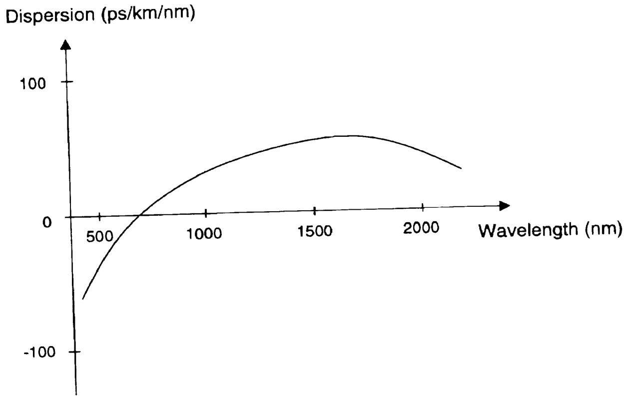

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**Fig. 15**

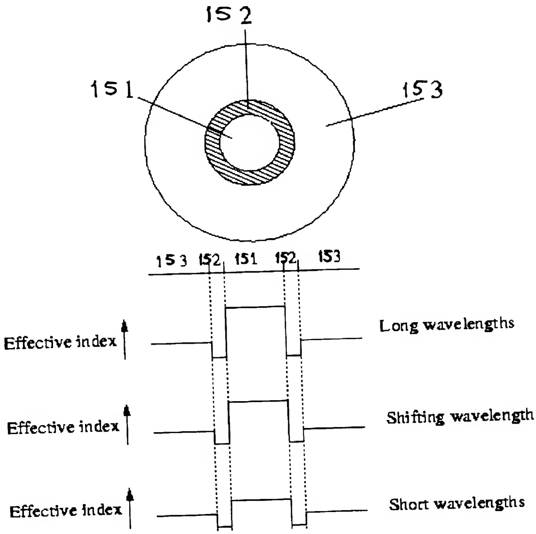

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Fig. 16

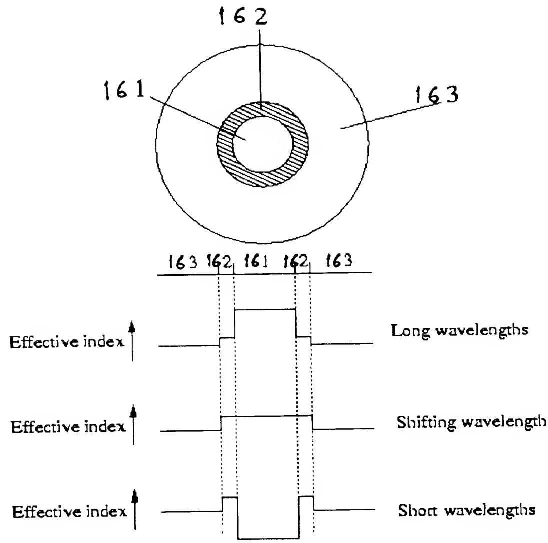

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**Fig. 17**

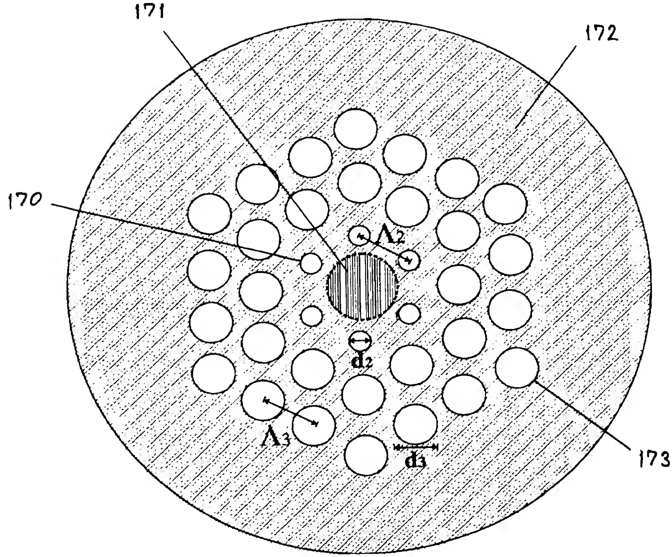

Fig. 18

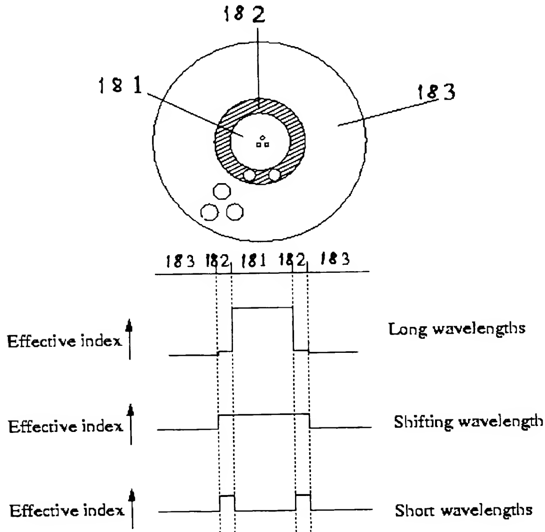
182
181
183
183 182 181 182 183
Effective index
Long wavelengths
Effective index
Shifting wavelength
Effective index
Short wavelengths

Fig. 19

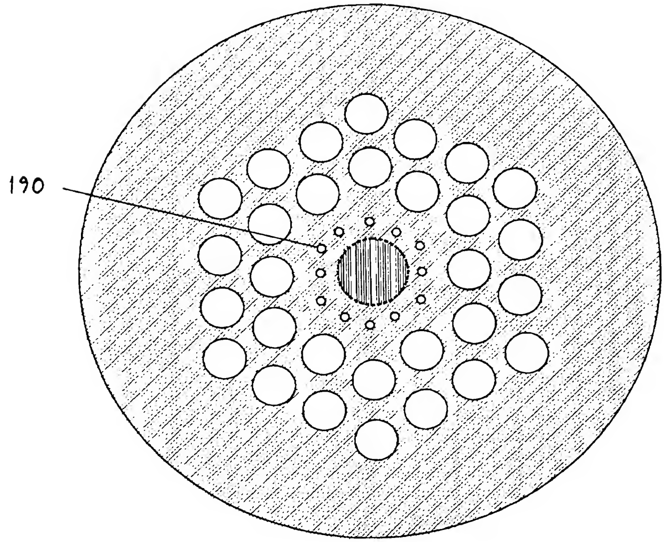

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**Fig. 20**

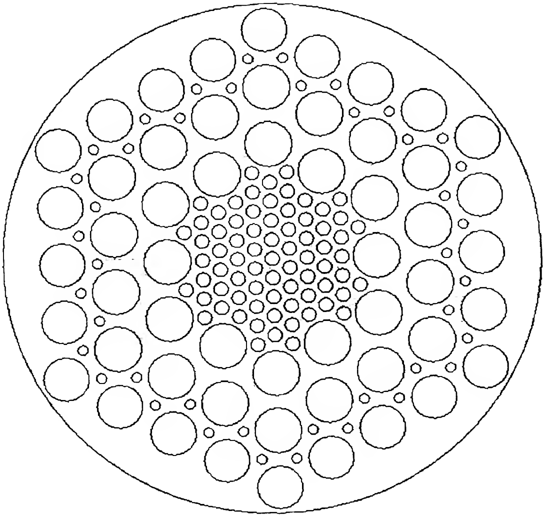

**Fig. 21**

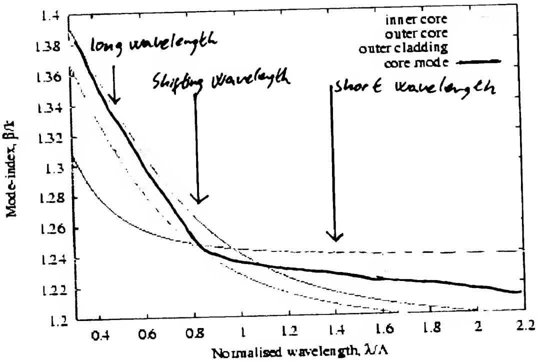
inner core
outer core
outer cladding
core mode
long wavelength
Shifting wavelength
short wavelength
Mode-index, β/k
1.4
1.38
1.36
1.34
1.32
1.3
1.28
1.26
1.24
1.22
1.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
Normalised wavelength, λ/Λ

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**Fig. 22**

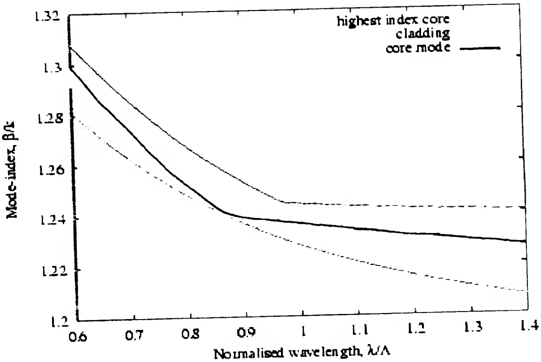

Fig. 23

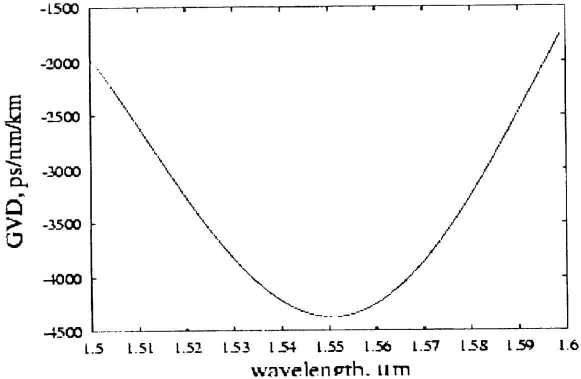
-1500
-2000
-2500
-3000
-3500
-4000
-4500
GVD, ps/nm/km
1.5
1.51
1.52
1.53
1.54
1.55
1.56
1.57
1.58
1.59
1.6
wavelength, μm

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Fig. 24

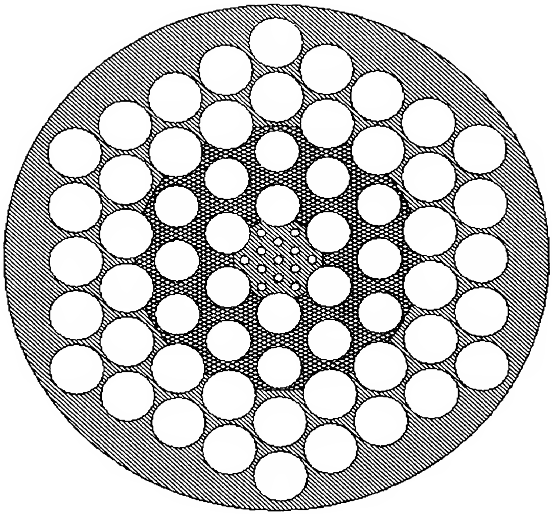

Fig. 25